Quantitative measurements of fast ions from CO_2 laser-produced plasmas

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(Received 21 December 1978; accepted for publication 27 February 1979)

The asymptotic behavior of the fast-ion energy spectra has been studied by using a Thomson parabola ion spectrometer to analyze ionic species produced by a 10.6-μm laser-produced polyethylene plasma. The use of cellulose nitrate film detectors has yielded for the first time quantitative information about the charge state and energy distribution of these high-energy ions as a function of laser energy and beam polarization.

PACS numbers: 52.70.Nc, 52.50.Jm, 42.60.Kg, 42.55.Dk

The velocity spectra of ions emitted from plasmas produced by intense short-duration laser pulses typically exhibit an anomalous fast-ion component.[1,2] Although it represents only a small fraction of the total ions produced, this component can nevertheless contain a significant fraction of the absorbed laser energy.[3] Thus, knowledge of the origin of these high-energy ions is not only imperative to the understanding of the interaction but also has strong implications for effective absorption, energy transport, and hydrodynamic stability of laser-fusion targets. Various mechanisms[4–6] have been proposed to account for fast-ion generation in an attempt to correlate them with the well-characterized two-temperature electron distribution deduced from x-ray emission measurements.[7] Moreover, application of a two-temperature isothermal rarefaction wave model[8] to the velocity spectrum of the ions can render information on θ_H and θ_e, the hot- and cold-electron temperatures respectively, and n_H/n_e, the hot–to–cold-electron density ratio. Experimentally, there is a general lack of quantitative data on ion-velocity spectra and their dependence on laser and focusing characteristics. We have therefore studied the asymptotic behavior of the fast ions, from plasmas created by intense (10^{14} W cm^{-2}) nanosecond CO_2 laser pulses utilizing an approach which permits quantitative information to be obtained about the charge state and energy distribution of these high-energy ions. In particular, we report the behavior of the fast-ion distributions as a function of laser energy and beam polarization.

A Thomson parabola ion spectrometer was used to analyze the ion species from a $(CH_2)_n$ plasma produced by the output of one arm of the COCO II laser system.[9] The laser system provided energies up to 40 J in a pulse of 1.5-ns (FWHM) duration which was focused onto plane massive targets by $f/2.3$ 20-cm-focal-length off-axis parabolic optics an an angle of 22°. The focal spot, limited by mirror imperfections, had a measured half-energy diameter of $\sim 110\,\mu$m. An on-line prepulse monitoring system detected no significant prepulse (less than $200\,\mu$J). The ion spectrometer[10] was placed approximately 1.3 m from the plasma along the target normal. Both the spectrometer and the target chamber were evacuated to 10^{-5} Torr to minimize the charge-exchange effects.[11] Cellulose nitrate film (Kodak LR115–type 2) was used to record the tracks of individual fast ions, and a semiautomatic Fourier transform technique[12] was employed to acquire quantitatively the energy distributions of all the ion species present in the plasma.

Figure 1(a) shows the complete H^+, C^{6+}, C^{5+}, C^{4+}, and C^{3+} energy distributions in the range $\sim$40–270 keV per charge. In Fig. 1(a) the H^+-to-ΣC^{n+} ratio is seen to increase steadily with increasing E/z. This result is consistent with that obtained with 1.06-μm laser-produced plasmas[13] and emphasizes the point that a multifluid description of the expansion is necessary for plasmas containing ionic species with different A/z. In a $(CH_2)_n$ plasma preferential acceleration of the protons by the much heavier carbon ions is to be expected. A persistent substructure, a feature also apparent in 1.06-μm experiments,[13] is observed when the energy spectra are obtained with sufficient resolution. This structure could be due to the variation of the pressure gradient on a subnanosecond time scale or the ionization and recombination effects being important during the ion acceleration phase[14] or the onset of the ion-ion streaming instability[15] between the protons and the carbon ions in the underdense plasma. The maxima observed in the C^{6+} and C^{5+} distributions match to within 10 keV. However, those of the C^{4+} and C^{3+} distributions appear at a higher E/z, suggesting that these ions may have been largely formed by recombination within the bulk plasma and/or charge exchange with the residual gases inside the target chamber and the spectrometer. Also apparent in Fig. 1(b) is the very definite upper velocity cutoff at $\sim 3.7\times 10^8$ cm s^{-1} for all the carbon-ion species.

The dependence of the fast-ion energy distributions on incident laser energy is shown in Fig 2. An increase in laser energy results in an increase in both the number of fast ions and the energy of the fastest ions. The distributions are also seen to developed more structure as the laser energy is increase, suggesting, the onset of the streaming instability mentioned earlier.

In Fig. 3, the fast-ion velocity distributions are shown for laser shots with s and p polarization. The isothermal rarefaction wave model of plasma expansion[8] predicts that for large ion velocities the asymptotic velocity distribution can

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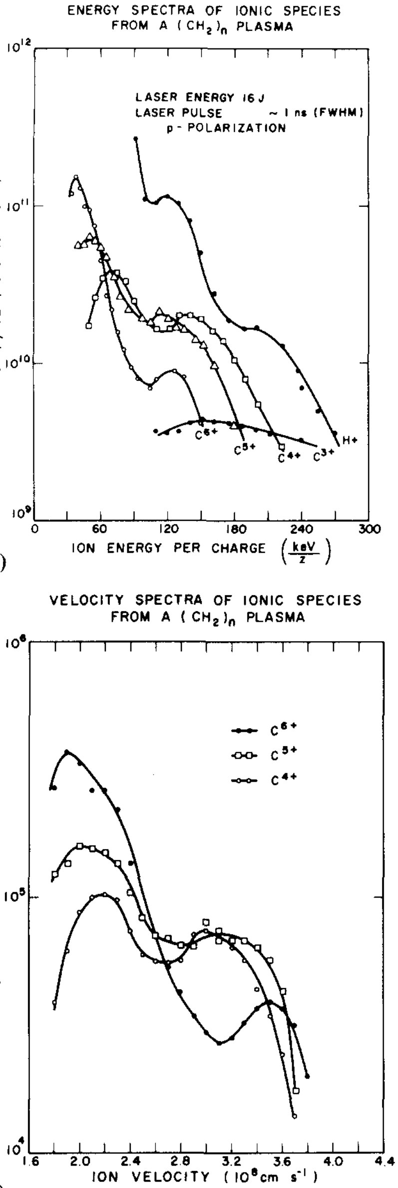

(a)

(b)

FIG. 1. (a) The energy distributions of ionic species from a polyethylene plasma and (b) the corresponding velocity distributions of the carbon ions.

be used to obtain C_s, the fast-ion acoustic speed, and, hence, the hot-electron temperature. The values of C_s deduced from these distributions gives values of θ_H between 9 and 15 keV for both p and s polarizations, which is reasonably consistent with a value of 9 keV obtained from x-ray continuum measurements. The main differences in going from s to p polarizations are that the absolute number of fast ions at a given energy is increased by almost a factor of 2 and the maximum ion energy is increased by a factor ~ 1.54.

Computer simulations of the electron distributions resulting from resonance absorption[16,17] in the presence of a steepened density profile suggest that θ_H scales weakly with $I\lambda^2$, where I is the laser intensity and λ is the laser wavelength. Interferometric measurements have shown that strong density profile modification and even cratering[18] occurs with both s and p polarizations at the high laser intensities, greater than 10^{14} W cm^{-2} used in these experiments.

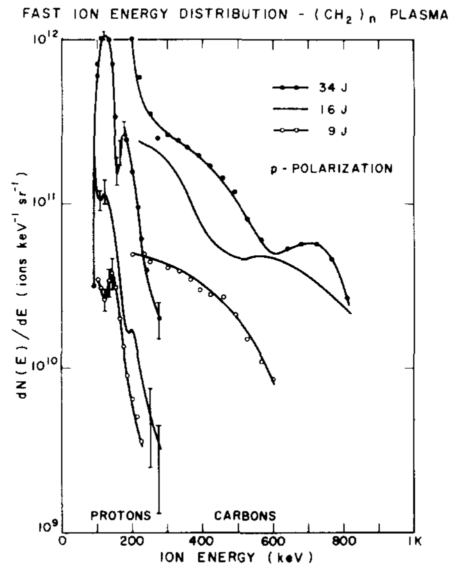

FIG. 2. The energy spectra of fast ions are plotted for three different laser energies.

These effects, together with the use of wide-angle focusing optics, result in the s-polarized beam having a component of the **E** vector in the direction of the density gradient. Thus, resonance absorption can be considered an important absorption mechanism for both p- and s-polarized beams. Absorption measurements have indicated that for the p-polarized beam approximately $40 \pm 5\%$ of the incident laser energy is absorbed, whereas for the s-polarized beam the fractional absorption is down to $25 \pm 5\%$.[19] Thus, in accounting for the differences in the distributions shown in Fig. 3, the increased absorption, together with the slightly higher incident laser energy for the p-polarized beam, produces a larger number density of hot electrons (and conse-

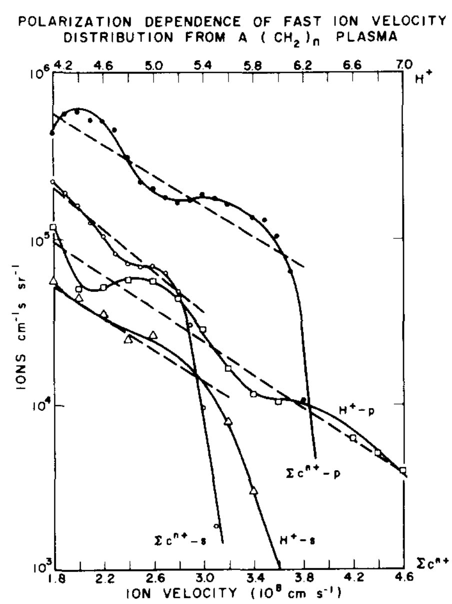

FIG. 3. Fast-ion velocity spectra for p- and s-beam polarizations. The ΣC^{n+1} represents the sum distribution of all the carbon-ion species present in the plasma. Note that the velocity scales for protons and the carbon ions are different. The hot electron temperatures are estimated from the slopes of the dotted lines.

quently fast ions) without increasing their temperature significantly compared with those produced by the *s*-polarized radiation.

According the isothermal rarefaction wave models of plasma expansion, a continuously decaying ion velocity distribution should be observed. However, the distributions obtained in these studies exhibit a rather sharp cutoff velocity. Departure from the ideal isothermal expansion would be expected if the quasineutrality condition breaks down in the underdense plasma (this will occur if the hot electron Debye length exceeds the density scale length) or if the hot-electron distribution, assumed to be a Maxwellian in the model, is truncated at some maximum electron energy.[20] Assuming resonance absorption is the important if not the dominant absorption mechanism in both *p*- and *s*-polarization cases, such a truncation of the hot electron energy distribution can be due to wave breaking limiting the amplitude of the resonantly excited electrostatic wave.

The authors wish to acknowledge valuable discussions with N.A. Ebrahim and M.D.J. Burgess, and thank P. Burtyn, G. Berry, and Y. Lupien for the continuing technical support.

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Effect of nitrogen-ion implantation on the unlubricated sliding wear of steel

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(Received 27 November 1978; accepted for publication 27 February 1979)

The effect of 30-keV nitrogen-ion implantation on the unlubricated sliding wear of type-38 NCD4 steel has been investigated. The effect of implants is seen to reduce the amount of wear for nitrogen doses above 10^{17} ions/cm^2. The reduction in the wear persists also after removal of a material thickness greater than the penetration depth of the implanted nitrogen ions.

PACS numbers: 81.40.Pq, 81.90. + c, 62.20.Pn, 46.30.Pa

Ion implantation has been used to improve resistance to wear, fatigue, and corrosion in both steels and other metals and alloys.[1] Wear measurements have been carried out by Hartley[2,3] and Hartley and Watkins[4] with a pin-on-disk wear tester for different combinations of steel alloys wearing one against the other. A reduction of the volumeteric wear rate of a factor from 20 to 30 has been observed for lighter loads using nitrogen implantations. More recently, Hirvonen *et*

